A Systematic Methodology to Underpin the CC® Process Using Calibrated BES Model

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ABSTRACT

This paper describes a theoretical framework for utilising whole building and reduced order calibrated BES models to underpin a systematic Continuous Commissioning® (CC®) process for building environmental optimisation and effective energy conservation. An investigation will be carried out focusing on all the stages of the CC process detailed in the CC handbook. A calibrated EnergyPlus Building Energy Simulation (BES) model will be developed initially to underpin the implementation of the CC process on a demonstrator building based in the National University of Galway (NUI Galway), Ireland. A process for reducing the calibrated EnergyPlus BES model to a reduced order Modelica based BES model that will support near real time analysis and provide functional support to the CC process during building operation is described.

INTRODUCTION

Buildings account for upwards of 40% of end energy use (Eurostat 2008). This is compounded by the fact that the global building stock does not reflect the expected design performance during operation (O'Donnell 2009). There are two main reasons for this; poor design of systems and poor management and maintenance of these building systems. There is however large scope for improved performance and reduction in energy usage and costs.

Building commissioning has emerged as the preferred method of ensuring that building systems are installed and operated to provide the performance envisioned by the designer (Liu, D. E. Claridge, et al. 2003). Building commissioning is defined as " the process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained according to the owner's operational needs" (Portland Energy Conservation, Incorporated (PECI) 1998). A number of institutions have published guidelines detailing the commissioning process with the same general goal (ASHRAE 1996; CIBSE 2001). During commissioning all the building HVAC components and systems must be verified to ensure that building performance in the operational phase of the Building Life Cycle (BLC) is as specified in the original design. This task is an instinctive heuristic process and often results in sub-optimal performance of the building systems during operation (O'Donnell 2008). Commissioning is predominantly a once off activity to ensure initial operation is as designed at the initial stages of building operation. The usage pattern during the BLC can often vary from the initial envisaged occupation pattern and a lack of customization to specific occupation trends and evolution in use can lead to reduced performance (Torrens et al. 2010). The evolution of building use over time combined with the lack of continuous monitoring can allow sub-optimal performance to go undetected. This culminates in increased expenditure for the building owner on two fronts. Firstly larger energy bills and secondly, studies have shown a reduction in productivity when the internal environmental conditions are not optimal for the occupants (Fisk & Rosenfeld 1997; Clements-Croome 2000; Sensharma et al. 1998). Combine the above facts with the global requirement to reduce carbon emissions in order to slow down global warming and the need to meticulously manage building energy consumption is glaring.

Continuous Commissioning® (CC®)[1] focuses on improving overall system control and operations in a facility to cater for its current utilisation. It is defined in the CC handbook as an ongoing process aimed at resolving operating problems, improving comfort, optimising energy use and identifying retrofits for existing commercial and institutional buildings and central plant facilities (Liu et al. 2002). The CC process has been demonstrated to maintain a high level of performance through continued follow up investigation and analysis of performance. Case-studies have shown that CC of buildings achieves savings of 20% or greater with payback often inside two years of the initial investment (D. E. Claridge et al. 1996; Deng et al. 2008; Hood et al. 2005; Turner et al. 2003; Liu et al. 1999). CC maintains savings through conducting regular follow up analyses of the building performance by a trained CC expert. If

[1] The terms Continuous Commissioning® and CC® are registered trademarks of the Texas Engineering Experiment Station, a member of the Texas A&M University System, an agency of the State of Texas. This mark is acknowledged, but will not be used for the remainder of this paper to enhance readability.

deterioration in building energy performance is detected then measures are recommended to restore the performance of the building. The BuildingEQ project in Europe has linked the CC process with legislation introduced to combat excessive building energy consumptions (EPBD), (Jagemar & Olsson 2007; EU 2002; Neumann & Jacob 2008). This identifies the global focus to make buildings more efficient throughout the BLC. CC also recognises BES as a vital tool in achieving optimal building performance (Bynum et al. 2010; Claridge, D.E. 2004; Song et al. 2004; Lee & D. Claridge 2002; Haves et al. 2001).

As every building is unique in its own right, there are numerous Energy Conservation Measures (ECM) which could be employed. It is difficult to intuitively know which solutions would be most effective and yield the greatest dividends. This makes it extremely desirable to be able to test plausible solutions to existing problems and possible optimisation strategies in a reliable manner throughout the CC process. Having a calibrated BES model available makes it possible to test ECM's so that they can be ranked on effectiveness and savings potential. The most effective measures can then be introduced initially and if some options prove fruitless they can then be eliminated. Calibrated BES models can also be used to improve energy performance by optimising building control strategies (A. Costa et al. 2009). This would allow for more effective use of time and labour. Calibrating a BES generally is a time consuming and difficult process due to the lack of quality and reliable information. If the calibration process of a whole building BES model was to run in parallel with the currently established CC process it would improve the efficiency of the CC process and improve the savings potential by testing the proposed CC measures in a verified model.

Traditionally BES calibration has been a heuristic process where key parameters were adjusted by an analyst in order to manipulate the model to better represent the building data available (Troncoso 1997). These adjustments are "highly dependent on the personal judgment of the analyst performing the calibration" (Reddy 2006). Commonly there are large holes in the measured data available from the Energy Monitoring and Control System (EMCS) and the missing data needs to either be assumed or estimated by the analyst (Raftery et al. 2009). To date there is no recognised formal calibration methodology. Raftery et al. has proposed a novel calibration methodology that is based on a hierarchical evidence assimilation process (Raftery et. al, 2011). Evidence is always taken from the most reliable source and as the model is iteratively brought through the calibration process. All stages of the model development and all changes to the model are recorded in detail utilising version control software. The evidence, on which all changes are based, is referenced and stored. This way all stages of the model are fully transparent and reproducible.

METHODOLOGY

This paper proposes to merge the development of a calibrated BES with the CC process to streamline and enhance the optimisation of building performance, this is shown in Figure 1 below. Both processes will be examined and linked in order to focus the development of both simultaneously. An exploration of the processes will reveal where they can be mutually beneficial and especially when carried out in tandem. The methodology will have its foundations in the CC process. The development of a Building Information Model (BIM) and a calibrated BES model will be incorporated into the CC procedure to allow them both to develop in tandem. This will allow for quicker development of the model and detailed investigation of ECM overall effectiveness. In the long term it is envisaged that a high fidelity model from EnergyPlus will be used to validate a lower fidelity model in Modelica. A high fidelity model would be computationally too expensive for real time simulation. The lower fidelity Modelica model would then be used coupled with the building EMCS to perform real time data analysis between simulated results from a calibrated model and data measured from the building in real time.

Phase 1: Stage 1

Potential target buildings are identified based on poor thermal performance or excessive energy usage. If the building HVAC features are not fully utilised this can also warrant further analysis. Information required here includes monthly utility bills, building size, function, occupancy schedules, O&M manuals etc.

As this is a preliminary stage of the CC process no concrete work will be done on the BIM. However it is practical to use this stage to compile information that can then be utilised when the drafting of the BIM begins. The CC process will only continue if there is deemed to be sufficient scope for improvement such as to render it cost effective within an acceptably short payback period. Geometric information that is required for stage 1 is the main useful information at this juncture. However occupancy schedules and O&M manual should be documented systematically.
These provide useful sources of materials information when assigning thermal properties to the building envelope. It is of benefit for both the CC process and the model generation process to have as much reliable information available as possible.

Phase 1: Stage 2

The outputs required from stage 2 of phase 1 are an audit report that will detail the major CC measures and the savings estimated from these measures. Any available data at a whole building or sub-metered level are analysed at this stage. The mechanical plans and control system documentation is analysed to identify areas where sub-optimal performance is evident.

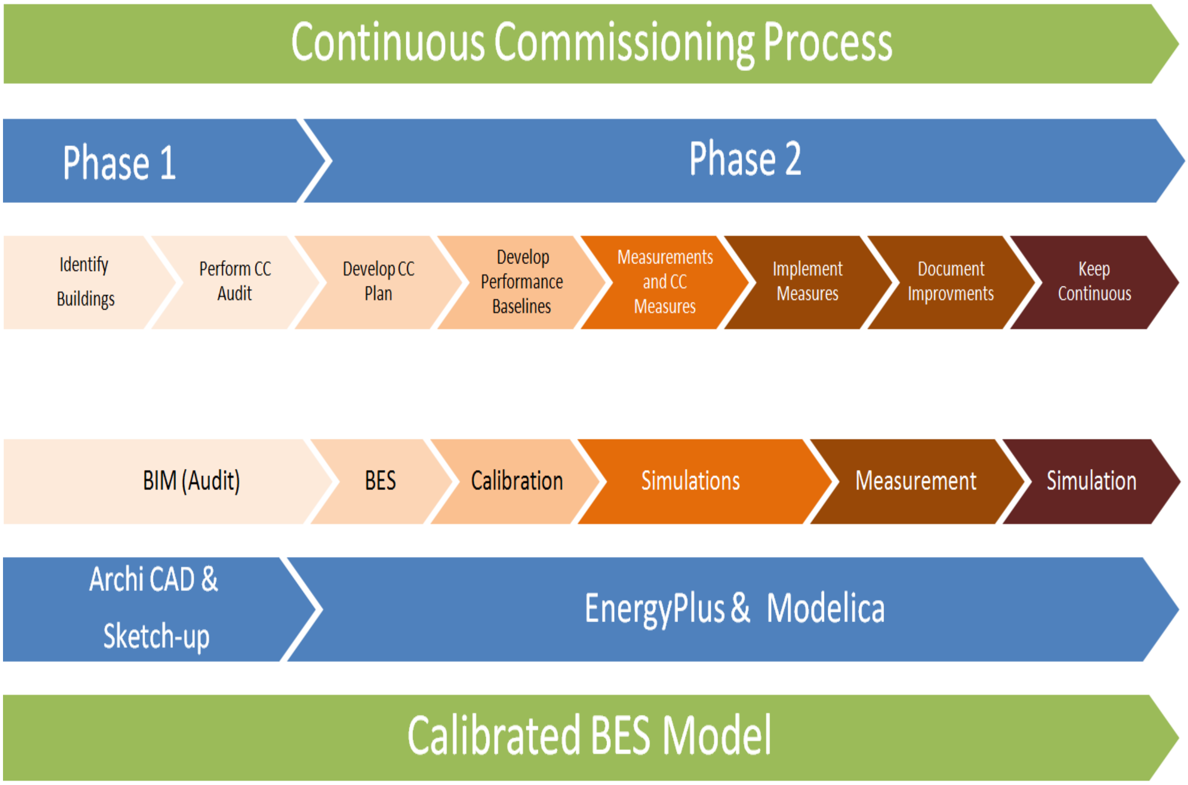

Figure 1: Process Flowchart

At this stage if there is clear indication that a contract will be signed it is possible to advance with the model. A comprehensive BIM can be drafted from the drawings collected in stage 1 which detail the building geometry. The BIM will contain details of the building geometry including the constructions and important material properties for the energy simulation. These material properties may be available in the O&M manual, online or if values can be taken from ASHRAE (ASHRAE 2009). There are two software tools which facilitate the development of the BIM - ArchiCAD and Sketch-up. The beneficial aspects of these software tools are that they are compatible with EnergyPlus. The more interoperability there is between software tools the better as this will reduce the need to duplicate work, saving time and resources.

Advantages of having the two processes running in parallel for stage 2 are the availability of a complete set of mechanical, electrical and, systems design documentation. These are required for identifying major CC measures and will be utilised in assembling the HVAC elements of the BES. The operating parameters, e.g. schedules and set-points, also obtained in this stage of the CC process are utilised in gaining the initial model and in the calibration process.

Phase 2: Stage 1

Once the contract is signed phase 2 begins. Stage 1 of Phase 2 is predominantly of a clerical nature. A clear plan is detailed which identifies the team and the various roles and responsibilities expected from each member.

At this stage the BIM model should be complete and efforts can be focused on developing the initial BES model. The BES model will incorporate the BIM completed during phase 1 and the various elements that make up the HVAC, electrical and lighting systems in the building. This stage is mainly about organisation and is an opportunity to progress the BES model. The BES model should be delegated to a member of the CC team during the team formation.

Phase 2: Stage 2

This stage of the process focuses on determining the current performance of the building. Any complaints elicited from the client/occupants regarding the building environment are documented. All data that is available from the EMCS is collected and analysed to give performance baselines for the building. This data should pertain to an extended period (at least 6 months or preferably a year) and include all utility and sub metered data. These performance baselines provide evidence of what energy is being consumed where and the profile of the consumption with time.

This stage of the CC process focuses on determining the actual performance of the building. It is then possible to start moulding the BES model into a calibrated BES model. Utilising the data obtained in developing the baseline performance, the building simulation can be manipulated using this data to mirror as closely as possible the building performance (Figure 1). The calibration procedure has been described previously in the introduction. The calibrated model should closely reproduce the baseline performance when simulations. ASHRAE Guideline 14 declares that a model can be declared calibrated when it has a mean biased error (MBE) of ±10% and root mean square error (RMSE) of ±30% for hourly data (ASHRAE 2002).

Phase 2: Stage 3

Stage three is where having a calibrated BES model will offer significant advantages rather than starting from stage 1 at this stage of the CC process. In stage 3 of phase 2 the objectives are to devise strategies and solutions to existing problems that the audit and baseline analysis reveal. Retrofit measures that require capital expenditure may also be identified and recommended as a CC measures. ECM's that that require capital expenditure are avoided as much as possible except where the payback period is deemed to be short enough to render the retrofit measures effective.

Utilising the previously prepared calibrated BES model the various solutions that are proposed are incorporated into the model individually and simulations run individually to test each separate proposed measure. The results from the model can then be analysed to check if the ECM's have had the expected effect on either the building environment or the building energy consumption and cost. Once the proposed measures have been checked they can be ranked in order of effectiveness based on the impact on building environment, the building energy consumption and cost. The most effective can then be recommended for implementation starting with the most effective. Comfort problems within the building are given a priority and then savings are pursued and achieved without compromising the comfort conditions for the building occupants.

Phase 2: Stage 4

Once the CC measures recommended have been approved for implementation work can commence on implementing the approved ECM's. Solutions to comfort problems with the building environment are implemented as the first priority. Then solutions relating to other issues and new proposals which will reduce the energy demand and energy expenditure within the building are introduced.

The measures implemented at this stage are to be based on the simulations carried out in the previously using the calibrated BES. During this stage the BES model can be employed to run further verification simulations on the CC measures that are to be introduced. Particular attention should be given to any CC measures that require capital expenditure to ensure these modifications will yield a sufficiently brief payback period. Once the final measures have been implemented the model should be updated to include all measures that are carried out and simulations run. The future performance of the building should mirror this in accordance with ASHRAE Guideline 14, under the same weather conditions of occupancy profile.

Phase 2: Stage 5

Once the CC measures are in place it is important to verify that the measures have been effective and conduct a follow up analysis which provides evidence that improvements have been made to both the indoor environment and the energy consumption and cost. The follow up analysis is carried out in the same manner as the initial analysis. Firstly the comfort conditions are documented under similar conditions to ensure a fair test. Then new performance baselines are compiled and analysed from data from the building EMCS. These are compared against the measurements taking at the start and changes in comfort and energy performance are documented.

The new performance baselines should also be compared against the simulated results of the final updated model (i.e. including all implemented ECM's) completed in the last stage. The model should be run again with an accurate weather file for the period of time being analysed. This will allow for a fair comparison between the simulated results and the actual performance. This will reveal if the building has performed as expected or if performance has trended downward with time after the measures were implemented. If there are discrepancies between the two sets of results outside of the accepted criteria set out by ASHRAE Guideline 14 this should be investigated unless there is an acceptable explanation.

Phase 2: Stage 6

The focus of stage 6 is to keep the commissioning continuous and maintain the internal building environment comfort of all the building occupants. This also targets keeping the building running optimally in relation to energy consumption. Furthermore additional measures are investigated to improve building performance. This is achieved by carrying out follow-up analysis of performance at regular intervals.

The calibrated BES can be used to investigate any new proposed measures before implementation as described in previous sections. The simulation results can also be used to investigate if the performance of the building is below the expected targets by comparing data from the EMCS to the simulated results.

CC and Real Time Fault Detection

Real time Fault Detection (FD) could be realised through the use of a calibrated reduced order model. The calibrated reduced order model would be developed using the high fidelity calibrated BES model as a baseline in conjunction with the EMCS data. If this was used in parallel with the EMCS measured data and compared it would be possible to identify large deviances from expected behaviour almost immediately. With the possibility of real time identification of deviations in performance behaviour it would allow the building manger to correct these issues promptly to allow optimum performance to be maintained throughout the building life cycle. Significant research is also being carried out in the area of fault detection and diagnosis (FDD) which is aimed at providing a platform to allow faults to be automatically detected (Katipamula & Brambley 2005). Torrens et al (2010) proposes a methodology which highlights the benefits of automated CC tools, which would reduce both the time and cost associated with maintaining building performance through regular building evaluation. This would also reduce the need for specific technical knowledge to allow building managers to operate without the help of outside expensive expertise (Torrens et al. 2010).

CASE STUDY

NUI, Galway Nursing Library

The Nursing library is a newly constructed building at the National University of Ireland, Galway.

Figure 2: Nursing Library NUI, Galway

Completed in 2009, it is a building dedicated education purposed relating to the nursing disciplines on campus. The three storey building houses a mix of study areas, computer rooms, meeting rooms, library space, and offices. The gross floor area is in the region of 700m^2(c.7550ft^2).

HVAC Systems

The building has a mixed mode HVAC system with a dedicated outside air system (DOAS) for ventilation and a combination of automatic and manually operated windows for natural ventilation in most of the building areas. The DOAS draws air through an earth tube to temper the air during times of extreme weather. The internal environment of the building is maintained by convective hot water baseboard heaters outside of the summer months. Campus-wide district hot water supplies all heating systems in the building. Stand-alone direct exchange units cool the computer rooms.

Using the whole building energy simulation package EnergyPlus it was possible to simulate these HVAC systems. Complexities in drafting the BES include the size of the building and the fact that there are zones within the building below ground. This will increase the impact of 2- and 3- dimensional heat transfer effects when compared to larger buildings. Also, wind driven natural ventilation pose modelling challenges.

Stock Information and Measured Data

The building is connected to the campus EMCS. This measures a number of points throughout the building. Measurements recorded include:

- Space Temperature (°C);
- Space CO_2 levels (ppm);
- Electrical Energy Consumption (kWh);
- Heat Energy Consumption (kWh).

Initial investigations revealed that data was being discarded every 10 days. The EMCS was modified to record all values to allow for the calibration of an annual BES. This commenced in April 2011.

The electrical panel also explicitly separates electricity consumption by end-use (e.g. HVAC, lighting and socket loads). Also, it should be noted that the location of the building ensures easy access for site surveys and further measurement.

The quality of stock information about the building is very high due to its recent construction, and the attention paid to the building during commissioning by IRUSE researchers at the National University of Ireland, Galway. A complete O&M manual is available which contains high quality as-built drawings and generous information on materials used in the building construction. However, a number of investigations were required to determine materials used in some parts of the construction. In addition, there is also a depth of information on the HVAC equipment, including O&M information and design information. This was available through the NUIG buildings and estates office.

Data and Audits

In addition to the metering discussed above, the following have now been installed;

(i) A weather Station measuring:

- Dry-bulb temperature;
- Relative humidity;
- Barometric pressure;
- Wind speed;
- Wind speed -3s gust;
- Wind direction;
- Global Solar Irradiance;
- Diffuse Solar Radiation;
- Barometric pressure.

(ii) Uni-directional infra-red people counter at sole building entrance measuring cumulative light beam interruptions.

(iii) Data Logger, measuring:
- Inlet/Outlet Low-Pressure Hot Water (LPHW) temperature;
- Ground Earth Tube Inlet/Outlet Temperature.

Despite all the information listed above, gaps in the required information were apparent. This was solved by undertaking an extensive building audit in line with the CC procedure. Surveys were conducted to measure and verify (where possible):
- Building materials & constructions;
- Building geometry;
- HVAC & plant equipment;
- HVAC schedules.

Regular surveys are carried out to identify patterns for:
- Electrical equipment & operating schedules;
- Lighting load and operating schedules;
- Occupancy schedules.

CC & BES Model development

As this is an in-house research project without a commercial client the initial organisational steps of the CC process have been largely by-passed. However investigation of the need for CC in the case study building did reveal that the indoor environment was often outside the accepted limits for occupant comfort. An initial CC audit also revealed that there were scheduling and operational problems with heat still being supplied even when temperatures were in excess of maximum acceptable set points. At present the process is in phase 2 stage 2. The performance baselines are being drawn up and calibration of the BES model has begun (Figure 1).

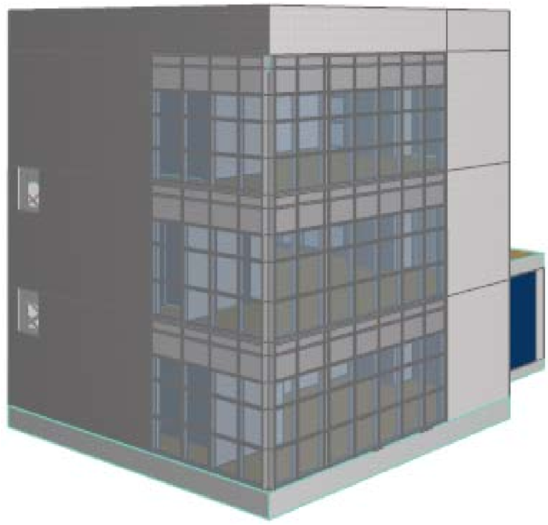

Figure 3: ArchiCAD BIM

To date efforts have focused on constructing the initial BES model in the context of the CC process. The information listed previously, collected from the EMCS, audits and O&M manual was used to construct the BIM (Figure 3) and initial BES. Figure 4 below demonstrates the process of obtaining a calibrated model.

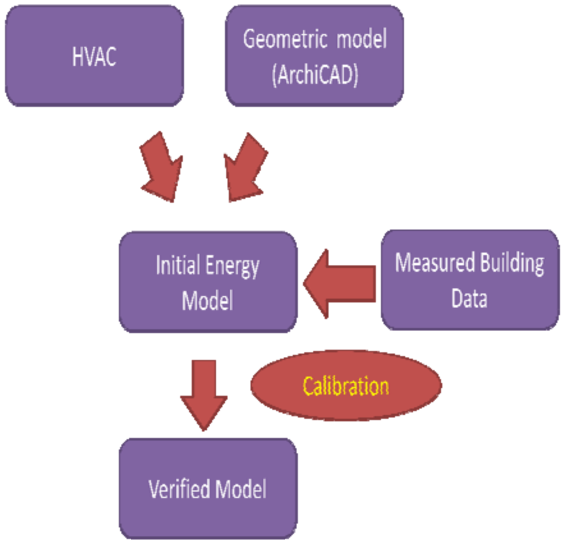

Figure 4: Model Generation Schematic

Using our initial best-guess estimates for building parameters based on the available evidence for the building, the BES model was simulated for two 10-day periods in April/May 2011. Results from the initial simulation runs of the model were then compared to available data from the EMCS. The Mean Biased Error (MBE) and the Root Mean Squares Error (RMSE) were then calculated. The results from the initial BES are displayed in the following section.

RESULTS TO DATE

At present the CC process is at phase 2, stage 2-developing performance baselines (Figure 1). Work to date on the CC process has revealed the following:
- Phase 1 Stage 1: Identify Buildings;
  - Poor thermal comfort: building often outside acceptable limits;
  - HVAC capabilities not fully utilised: Earthtube and automatic windows not operating optimally.
- Phase 1 Stage 2: CC Audit;
  - Audits previously mentioned have been performed and these activities are on-going.
- Phase 2 Stage 1: CC Plan;
  - Data collection has begun for analysis and calibration.
- Phase 2 Stage 2: Baselines:
  - Initial short term data (2-3 months) analysis has begun;
  - A year’s data will be collected for calibration.

The initial BES model has been constructed and the initial results to date are presented below. The graphs below display different performance metrics. They compare data taken from the initial BES model and data taken from the EMCS. The graph in figure 5 below shows the electricity consumption in kWh for the beginning of May. The results are a good fit for the initial model. This reflects the meticulous nature of the lighting and equipment audit undertaken.

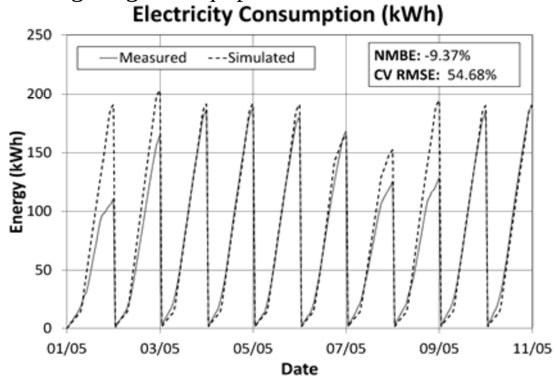

Figure 5: Electricity Consumption (kWh)

The graphs in Figures 6 & 7 show heat energy consumption (kWh) and zone mean temperature (°C). It is apparent from these results that there are significant errors with the simulated model data at this stage.

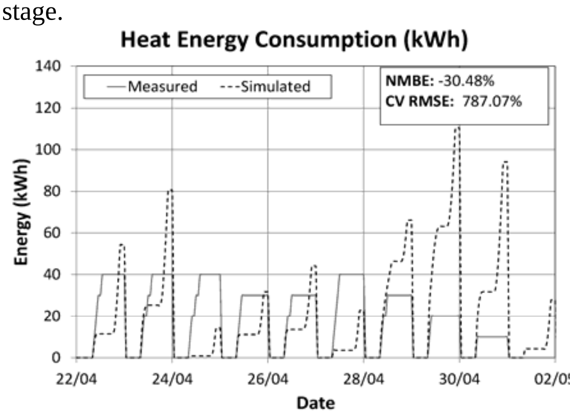

Figure 6: Heat Energy Consumption (kWh)

However lessons can be learnt from these initial simulations as to possible sources of error in the model. A steep decline in zone mean temperature (Figure 7) is evident at 22:00 every day. This would indicate excessive heat loss from the model building envelope.

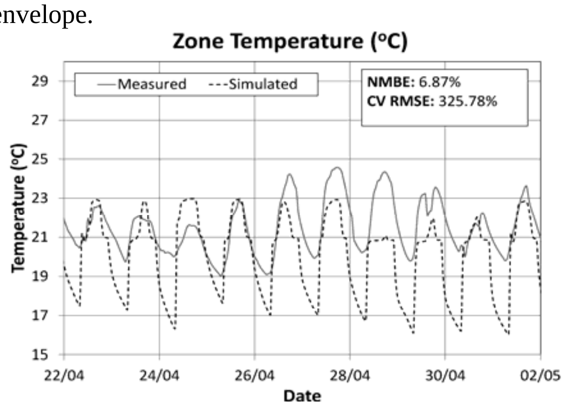

Figure 7: Zone Mean Temperature (°C)

ASHRAE Guideline 14 2002 declares models to be within calibration when they have a MBE of ±10% and RMSE of ±30%.

The model clearly requires further refinement and this will be carried out using data for extended periods from the building BMS and further building audits where the requirement is identified. The model development will be discussed further in below.

CONCLUSIONS

This paper proposes a methodology that will use the already established CC process and underpin it with the development and utilisation of a calibrated BES model. The calibration will be completed using a novel evidence based iterative process (Raftery et. al, 2011). Once the model is within the criteria specified by ASHRAE Guideline 14 it will be declared calibrated.

The construction of an initial BES model and the subsequent calibration process are incorporated into the initial stages of the CC process. By executing the two processes in parallel they will be mutually beneficial. During the initial stages information required for one process can be shared between the two. When baselines are being developed these can be used to calibrate the model too and building audits can be used to collect further calibration information.

Once the model has been calibrated to the required level of accuracy based on the evidence collected it can be used as a reliable representation of actual building performance. This will facilitate reliable testing of proposed CC measures, for example testing of new operating strategies and installation of new equipment, thus allowing the most effective internal environmental solutions and ECM's to be implemented. Effective and conclusive testing of CC measures would allow for optimal performance to be achieved and maintained in a structured and effective testing approach. Streamlining of the CC process would save on both the time and resources expended to achieve optimal performance.

FUTURE WORK

Future work will focus on completing the model calibration to measured data over 12 month period. The model will be declared calibrated when it fits within the limits declared be ASHRAE Guideline 14. This will then be employed in parallel with the CC process where various ECM's will be tested and recommended based on simulation results. The calibration process will follow the iterative evidence based procedure (Raftery et. al, 2011). This will be done by performing numerous simulations and refining the model with data from the hierarchical evidence tree, BMS/sensor data, spot measurement, as-built drawings, etc. ECM's expected at this stage include schedule set point optimisation and calibration of sensors that have been identified as giving faulty readings. This should allow for design operation of the automatic system which is currently switched off due to lack of confidence by staff in its operation. Optimisation of the heat exchanger linked to the earth tube is also expected to be a viable ECM.

In order to keep commissioning continuous a lower fidelity model using Modelica will be developed and verified against the calibrated EnergyPlus model. This will be investigated for use in real time simulation and compared to real time data measurements from the EMCS. If practical this would allow for real time fault detection by way of manual fault detection of sub optimal building performance. If faults were detected quickly then CC measures could be identified when the problem occurred and the problem would have minimal effect on building performance.

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